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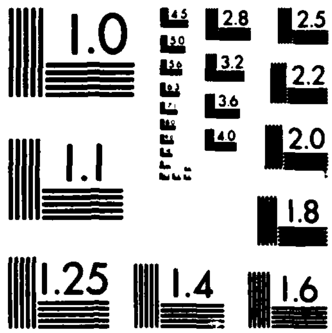

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I. RESEARCH PROGRESS

A. EXPERIMENTS (UCLA)

The high energy, axis-encircling electron beam produced by our TE_{111} gyro-resonant accelerator has been used to drive two varieties of high cyclotron harmonic amplifiers, the high harmonic gyro-klystron and the high harmonic gyro-TWT. The gyro-klystron has been tested in three configurations. The first was a simple two cavity gyro-klystron where the energy of the rotating beam is modulated in the buncher cavity. Bunches develop in the drift tube and radiate in the catcher cavity. The fifth harmonic device yielded a gain of 20 dB and a saturated output power of 90 W. Experimental results have been compared favorably to both small signal analytic theory and large signal numerical simulation in the manuscript, "A High Harmonic Gyro-Klystron Amplifier: Theory and Experiment," published in Int. J. Elec. 57, 1151 (1984). A multi-cavity system can be expected to yield considerably more gain because intermediate cavities will enhance the bunch formation. Using the same overall length as the two cavity device, the four cavity gyro-klystron yielded a gain of 37 dB, but saturated at roughly the same output power. Results have appeared in the manuscript, "Theory, Design and Operation of Large Orbit High-Harmonic Gyro-Klystron Amplifiers," published by IEEE Trans. Plasma Science 13, 435 (1985). In an effort to increase the output power the overall length was doubled and the magnetic field was reconfigured to allow a lower $\alpha(=v_\perp/v_\parallel)$ e-beam to be produced. The power level increased to 0.6 kW corresponding to a conversion efficiency of 6%. In addition, the gain increased to 45 dB. The axial velocity diagnostic was operable for this last experiment, allowing quantitative comparison between theory, simulation and experiment. Recent results are described in the manuscripts, "A Four Cavity, High Harmonic Gyro-Klystron Amplifier," by D.S. Furuno, D.B. McDermott, Haibo Cao, C.S. Kou, N.C. Luhmann, Jr., P. Vitello and K. Ko, and "Operation of a Large Orbit, High Harmonic Multicavity Gyro-Klystron Amplifier," by D.S. Furuno, D.B. McDermott, N.C. Luhmann, Jr., P. Vitello and K. Ko, submitted for publication in the International Journal of Electronics and IEEE Transactions on Plasma Science, respectively.

Though the gyro-klystron has displayed very high gain, it suffers from being a narrow band amplifier. The bandwidth is determined by the Q of the cavities. Their loaded Q value of roughly 1000 yielded a bandwidth of roughly 0.1%. A gyro-TWT has the advantage of a broad bandwidth. We have operated an eighth harmonic gyro-TWT near 16.2 GHz which displayed a gain of 10 dB, a bandwidth of 4% and a saturated conversion efficiency power of 0.5 kW which corresponded to an efficiency of 1.5%. It must be noted that it was a true transmission type TWT and not the usual reflection amplifier. A considerable amount of effort was spent on the modulator for the input rf source, a high power Ku-band coupled cavity TWT. The solenoid for the gyro-TWT was lengthened by 5 pancake coils while maintaining its axial homogeneity in the TWT region to within 1%. Though it reduced the device's gain the accelerated beam's axial velocity was boosted from 0.15 c to 0.30 c by placing the TWT in a region of lower magnetic field than in the accelerator. This was motivated by the fact that a larger $v_\parallel$ enhances the stability of the amplifier.

The most critical element of our harmonic gyro-TWT was the coupler, a TE_{n1} wave launcher. It is simply fundamental mode waveguide bent around the interaction tube in the azimuthal direction with many holes coupling the two structures. Dimensions must be chosen so that the axial wavelength in the guide is equal to the transverse wavelength of the TE_{n1} mode at the wall of the tube (D/n, where D is the tube's inner diameter). The directivity of the wave is determined by the placement of a shorting plate behind the coupler. The transmission of the coupler must be quite good to avoid oscillation due to reflections. Our coupler launched a circularly polarized TE_{n1} wave with a transmission of 85%, which permits the operation of the amplifier up to a gain of $(\frac{1}{1-0.85})^2 = 45$ or 16.5 dB. At this gain the tube will oscillate.

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Accurate measurement of the axial velocity is required to meaningfully compare experimental results to theoretical predictions. For example, the gain of the four cavity gyro-klystron is inversely proportional to $v_\parallel^{12}$ and the growth rate of the gyro-TWT is inversely proportional to $v_\parallel^{2/3}$. We built a new high resolution diagnostic to determine the axial velocity and velocity spread by measuring the beam's pitch. It is comprised of three plates mounted perpendicular to the magnetic field lines. A small radial slot aperture is placed in the two plates closest to the electron source and the gap between these two plates can be adjusted. The last plate, a Faraday Cup, measures the remaining current. Electrons, which trace out a helical path, pass through *both apertures only* if the distance between the two plates is an integral number of the fundamental length of the helix. The ratio $v_\perp/v_\parallel$ is determined by the distance between the maxima of the transmitted current, and the width of a high order peak yields the velocity spread ratio, $\Delta(v_\perp/v_\parallel)$.

A peniotron is of interest because it is potentially very efficient since <u>all</u> electrons lose energy. A high harmonic peniotron driven by our rf-accelerated axis-encircling electron beam has been investigated. It radiates into a TE_{nmp} mode at the frequency, $\omega = (n-1)\Omega_c$. A third harmonic TE_{411} peniotron was tested. Oscillation at 24 GHz was achieved by using a relatively long cavity and by using a trim coil to slow the electrons as they enter the "mirror" field. The length of the interaction cavity was 10.16 cm and its radius was 1.06 cm. This cavity was also longitudinally sliced twice (orthogonal cuts) to suppress the TE_{111} fundamental gyrotron interaction, essential since $q_{11} \approx q_{43}/3$. The device yielded only 2 W. We believe the early saturation occurred due to a competing gyrotron interaction. The (n-1)th harmonic TE_{n11} off-axis gyrotron interaction has been shown by P. Vitello to be approximately equal to the strength of the peniotron interaction for our parameters ($\Delta r_c/a \approx 0.05$).

A new RF accelerator cavity with improved coupling has been successfully tested. It avoids the loading problems associated with the earlier accelerator. Optimum coupling occurs when the waveguide fields overlap with just one component of the cavity field. Multiple coupling occurred in the original accelerator. The electric field of the waveguide coupled to the radial electric field in the cavity <u>and</u> the longitudinal magnetic field of the waveguide coupled to the longitudinal magnetic field of the cavity. In the new accelerator the coupling is purely magnetic. Here, the transverse magnetic field of the waveguide couples to the azimuthal magnetic field of the cavity. Now, due to the change in the coupling geometry, the measured peak efficiency is in excess of 50%, whereas the old value was only 15%. Furthermore, the theoretical and experimental study of the gyro-resonant RF accelerator has been completed and the manuscript, "Production of Relativistic, Rotating, Electron Beams by Gyro-Resonant RF-Acceleration in a TE_{111} Cavity," published by the J. of Applied Physics <u>58</u>, 4501 (1985).

The output frequency of gyrotrons and peniotrons can be increased by operating at a higher harmonic. However, because both the interaction strength and device efficiency decrease for increasing harmonic numbers, an effective limit exists for n ($\approx$15). To increase the output frequency, one must then increase the frequency of the accelerator and the strength of the magnetic field. We have partially constructed a higher frequency *accelerator* test stand. A 50 kW, 33 GHz magnetron has been combined with a modulator and successfully tested. A high-field superconducting solenoid and power supply was purchased . The vacuum system system and support table have been assembled. This will allow experiments designed to produce 1 kW at 100-300 GHz to be performed.

B. THEORY

<u>1. UCLA</u>

An analysis of the two-cavity gyro-klystron amplifier was performed, yielding an explicit expression for gain. The theory was confirmed experimentally within the limits of uncertainty. Verification of the theory was complicated by the fact that the gain depends very strongly on parameters which are not known to arbitrary accuracy. For example, the gain is inversely proportional to the fourth power of the axial velocity. An uncertainty of 25% for this parameter yields an uncertainty of 3 dB for gain.

Extending the two-cavity analysis to describe a multi-cavity amplifier was trivial once we realized that an n-cavity amplifier can be approximated by (n-1) two cavity amplifiers with the intermediate cavities acting as the catcher for the preceeding cavity and the buncher for the following cavity. This reasoning implies that gain for a multi-cavity is an even stronger function of the relevant parameters. For example, in our four cavity gyro-klystron amplifier the gain is inversely proportional to the twelfth power of the axial velocity. It became even more important to construct a high quality diagnostic for this parameter. Thus we built the beam pitch analyzer.

Analytic derivations of harmonic gyro-TWT gain had already appeared in the literature before we began our research. Gain is determined by a fourth order polynomial. We have begun parameter studies of small-signal linear gain by solving this equation for the experimental conditions appropriate to a gyro-resonant RF-accelerated electron beam (moderately low current, high transverse velocity, low longitudinal velocity, v_z). The paramount problem of operating a gyro-TWT with a beam with low $v_\parallel$ is oscillation. Operation of the eighth harmonic gyro-TWT with a beam directly from the accelerator would have yielded very high gain (0.4 dB/cm), but the uniformity of the magnetic field would have to have been kept within 1% to avoid an absolute instability. We decided to suffer the loss of gain (to 0.2 dB/cm) by increasing the axial velocity (to 0.3 c) by employing a magnetic taper because it significantly increased the allowable tolerance for magnetic uniformity. After taking the coupling loss of 9 dB into account the measured gain agreed very well with the predicted small signal gain.

2. SAIC

To augment earlier work which found the start of oscillation current for an axis-encircling electron beam, an analytic derivation of the high-harmonic gyrotron and peniotron interactions for off-axis electron beams has been completed. This is important because realistic beams have a finite radial thickness and are unavoidably misaligned to some degree. The dependence of the start-oscillation current on miscentering has been found. The start-oscillation current for the TE_{n11} mode from an nth harmonic gyrotron interaction or an (n-1) th harmonic peniotron interaction is inversely proportional to $J_0(q_{n1}\Delta r_c/a)$, where Δr_c represents the offset of the guiding center from the axis, a is the cavity radius, and q_{n1} is the first zero of the nth order Bessel function.

This study has also yielded a new physical interaction. An off-axis beam can interact with an nth-order azimuthal mode not only at the nth cyclotron harmonic, but also at many neighboring harmonics. This occurs because electrons with off-axis guiding centers rotate through the TE_{n11} nodes faster (slower) when they are near (far from) the axis, and therefore more able to emit at higher (lower) harmonics. Unfortunately, this effect complicates peniotron operation because the (n-1)th harmonic gyrotron interaction may overshadow the weaker peniotron interaction. Results were published in the papers, "Theory and Numerical Modeling of a Compact, Low-Field High Frequency Gyrotron," by P. Vitello, W. Miner and A. Drobot, IEEE Trans. MTT 32, 373 (1984); "Cyclotron Maser and Peniotron-Like Instabilities in a Whispering Gallery Mode Gyrotron," by P. Vitello, IEEE Trans. MTT 32, 917 (1984); and "Theory and Numerical Simulation of a Compact, Low Field, High Frequency Gyrotron," by P. Vitello, W. Miner and A. Drobot, Int. J. IR and mm-Waves 5, 507 (1985).

Numerical simulation focused on high-harmonic gyrotron and peniotron oscillators, high-harmonic two and four cavity gyro-klystron amplifiers and the high-harmonic gyro-TWT. Simulation is primarily concerned with optimizing the efficiency of the energy transfer. The dependence of the efficiency of a tenth harmonic oscillator on energy, axial velocity, cavity length, and guiding center mismatch was compared with estimates determined by phase-trapping. The interaction saturates when electrons slip 180° relative to the wave, corresponding to an efficiency of

$$\eta = \left(\frac{\gamma}{\gamma-1}\right)\frac{\pi v_\perp}{\omega L} \qquad (1)$$

By mistuning the starting conditions relevant to an rf-accelerated beam a peak efficiency could be found more than twice the value given by Eq. (1). The dependence of η for low energy beams is well described by Eq. (1), but it shows no dependence on energy for $\gamma>1.4$. The dependence of efficiency on axial velocity is very similar to its dependence on the inverse of the cavity's length. The important parameter is the time spent by the electrons in the cavity, equal to $L/v_\parallel$. Interestingly, the efficiency from simulation actually falls off for very short interaction times. Otherwise, Eq. (1) is satisfied. In addition to the start oscillation current being adversely affected by off-axis electrons, the efficiency decays as Δr_c increases also. The efficiency is reduced to 40% of its peak value for an off-axis beam with $\Delta r_c/a = 0.2$. We have found that the optimum efficiency of a tenth harmonic gyrotron with a 250 keV beam is 10%.

The gyro-peniotron oscillator has excellent potential for development as an extremely high efficiency microwave device. The price which one must pay for the peniotron interaction is the need to be extremely careful in designing the system in order to avoid competition from electron cyclotron maser excitation of other modes, and peniotron absorption and electron cyclotron maser interference within the desired mode. Using the general linear theory developed for smooth walled cylindrical gyrotron oscillators, we have studied start oscillation and mode competition between the desired peniotron interaction driven mode and unwanted electron cyclotron maser modes. Both the whispering gallery TE_{n11} modes interacting with axis-encircling beams and the first harmonic TE_{021} mode interacting with a non-axis encircling beam whose guiding center was placed at the radial null of the RF field ("conventional" peniotron geometry) were investigated. Mode competition from other modes was studied for a wide range of beam and cavity parameters. The results of this study indicate that competition for the gyro-peniotron can be avoided for TE_{211} and other low order whispering gallery modes when an axis-encircling electron beam is used and are described in the manuscript, "Mode Competition in a Gyro-Peniotron" by P. Vitello and K. Ko, published in IEEE Trans. Plasma Science 13, 454 (1985). Mode competition can not be easily avoided for an off-axis beam interacting with the TE_{021} mode. The TE_{021} mode is overwhelmed by the other modes and this is the geometry usually considered for a peniotron!

A second stability issue which was considered, after it had been determined that a peniotron emission mode was free from competition from other modes, was the question of interference within the mode itself from competing interactions. This is very damaging because whereas competition between different modes can be avoided by building a special cavity that destroys all but the desired mode, competition between different interactions cannot be suppressed. The dominant competing interactions come from the electron cyclotron maser emission and absorption, and from peniotron absorption. For an axis-encircling beam with no spread in guiding center interacting with a TE_{n11} mode, peniotron emission occurs at the (n-1)th harmonic, peniotron absorption occurs at the (n+1)th harmonic, and electron cyclotron maser emission and absorption fall at the nth harmonic. The analytical linear theory was used to determine the ratios of these interactions as a function of guiding center mismatch. Electron beam guiding center spread effects can be reduced if one uses low order azimuthal and radial (n,m) modes, moderate values of $\beta_\perp$ and $\beta_\parallel$, and short cavities.

A study was also conducted for nonlinear saturated efficiencies for the gyro-peniotron oscillator. Again, axis-encircling beams interacting with TE_{n11} modes were studied. For no spread in the beam guiding center or axial velocity, optimized efficiencies of over 93% were obtained with the TE_{211} mode. This corresponds to loss of more than 99% of the beam initial transverse energy. The ability to achieve such high efficiencies was found not to be sensitive to a spread in the axial velocity, but was sensitive to guiding center spread. A careful analysis of beam and cavity parameters has lead to a greater than 80% efficiency design "window" for the TE_{211} mode which is free from mode competition and interference, and which puts realistic constraints on the beam parameters ($\Delta r_c << r_\perp$ and $\Delta\beta_\parallel \leq 0.20\beta_\parallel$).

The gyro-klystron numerical model written by Prof. K.R. Chu was used by SAIC to calculate self-consistently the RF amplitude and phase in a multiple cavity system and supercedes the initial non-self-consistent numerical code written by P. Vitello, which yielded the data for the manuscript, "Analysis of a Low Magnetic Field TE_{m11} Gyro-Klystron Amplifier" by P. Vitello, published by Int. J. Elec. 57, 1162 (1984). This model determines as well the electron beam modified resonance frequency of the cavities. Drive frequencies other than the buncher cavity resonance frequency can be used to study stagger tuning. The modes can be either linear or circular polarized, and the cavities may be coaxial cavities. A Gaussian spread in the beam axial velocity and a uniform spread in guiding center is included in the model to simulate realistic beams. Currently the model is being extended to use exact cold cavity RF fields in place of the ideal cavity fields which ignore the cavity drift tube openings.

Calculations have been made of gain and efficiency as a function of the electron beam current, the input power, the initial velocity ratio α, the initial spread in $\beta_{\parallel}$, and the spread in guiding center Δr_c for the UCLA two and four cavity gyro-klystron experiments. The modeling has studied the weak field gain regime, the transition to infinite gain as the start oscillation current threshold is approached, and the high field saturation of the gyro-klystron. Good agreement with experimental data has been found for the two and four cavity theoretical and experimental results of the dependence of the gain on current. The code has demonstrated the insensitivity of the small signal gain to a spread in the axial velocity when the gyro-klystron is operated exactly at resonance ($\omega = n\Omega$). Indeed, due to the existence of slow electrons which interact more strongly with the wave, the gain can even be enhanced by a spread in axial velocity. For $\omega = n\Omega$ (x=0), all electrons will enter the catcher at the proper phase irrespective of their axial velocity. Therefore, no phase mixing occurs at resonance. The requirement on axial momentum spread for gyro-klystron operation off resonance is

$$\frac{\Delta p_{\parallel}}{p_{\parallel}} << \frac{L_c}{|x| L_d} \qquad (2)$$

where L_c is the cavity length, L_d is the drift tube length, and x is the mistuning parameter of the order of unity. Axial velocity spread can be ignored since gyro-klystron gain is strongest for $x \approx 0$.

A nonlinear self-consistent numerical code developed by Ganguly and Ahn at NRL for the conventional fundamental mode gyro-TWT was adapted for the high harmonic gyro-TWT. The model allows for tapering of both the magnetic field and the waveguide cross-section along the axial direction. We have used the model to analyze the UCLA high-harmonic gyro-TWT experiments. The system's characteristics such as the growth rate, the instantaneous bandwidth, and the sensitivity to axial velocity spread and to cavity and magnetic field tapering have been calculated. The numerical code not only gives the growth rate, it also gives the coupling loss into the other nongrowing modes. Nonlinear saturation has also been determined as a function of beam and cavity parameters.

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